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A METHOD TO INCREASE OPTICAL TIMING SPECTRA MEASUREMENT RATES USING A MULTI–HIT TDC

W.W. Moses
Lawrence Berkeley Laboratory, University of California, Berkeley, CA

Abstract

A method is presented for using a modern time to digital converter (TDC) to increase the data collection rate for optical timing measurements such as scintillator decay times. It extends the conventional delayed coincidence method, where a synchronization signal "starts" a TDC and a photomultiplier tube (PMT) sampling the optical signal "stops" the TDC. Data acquisition rates are low with the conventional method because ε, the light collection efficiency of the "stop" PMT, is artificially limited to ε≈0.01 photons per "start" signal to reduce the probability of detecting more than one photon during the sampling period. With conventional TDCs, these multiple photon events bias the time spectrum since only the first "stop" pulse is digitized. The new method uses a modern TDC to detect whether additional "stop" signals occur during the sampling period, and actively reject these multiple photon events. This allows ε to be increased to almost 1, which maximizes the data acquisition rate at a value nearly 20 times higher. Multi–hit TDCs can digitize the arrival times of *n* "stop" signals per "start" signal, which allows ε to be increased to ≈3*n*/4. While overlap of the "stop" signals prevents the full gain in data collection rate to be realized, significant improvements are possible for most applications.

Introduction

This paper describes a method to increase the data collection rate (and thus reduce the collection time) for measuring optical timing spectra using the delayed coincidence method of Bollinger and Thomas [1]. Data collection rate increases of an order of magnitude can be realized with this new method, so it is especially useful when a series of measurements are necessary, such as when measuring the temperature dependence of the decay time of a scintillator.

The proposed method is an extension of the delayed coincidence method of Bollinger and Thomas [1], which was originally devised to measure the fluorescent decay time of scintillators. This method allows an extremely accurate measurement to be made with relatively simple equipment, and so has also been applied to a number of other situations that measure the time spectra of optical signals. Unfortunately, the data collection rate with this method is usually low, frequently on the order of one data point per second when performing scintillator lifetime measurements. As an accurate measurement typically requires a minimum of 100,000 data points, collection times are usually on the order of days. The proposed method can reduce this acquisition time to a few hours without affecting the data quality.

While the time dependence of any optical signal can be measured with the delayed coincidence method, this paper describes a single application of the method (the measurement of a scintillation decay time) for simplicity. However, the methods described herein can be applied to any measurement using the delayed coincidence method.

Methods

Delayed Coincidence Theory

Before presenting the new methods, I will describe the sampling scheme employed by the conventional method by presenting an intuitive approach to measuring a scintillation decay time,

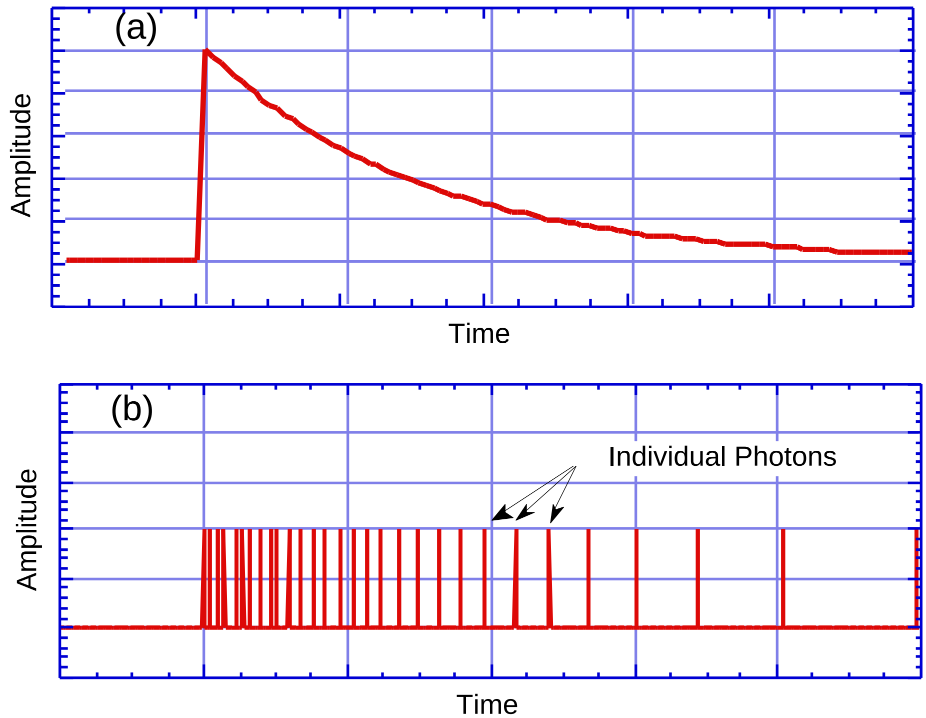

Figure 1: (a) Typical scintillator intensity versus time curve. (b) The arrival time of the individual photons responsible for (a).

showing the limitations of this approach, and demonstrating how the delayed coincidence method circumvents these limitations.

Figure 1a shows the luminous intensity of a scintillator resulting from an instantaneous excitation, which typically is a prompt increase at the time of excitation followed by a decay with time. The quantity that we are trying to obtain is a mathematical description of this decay in intensity with time. The obvious approach for obtaining this data is convert the optical signal to an electrical signal with a photomultiplier tube, then digitize the output voltage (*i.e.* the intensity versus time curve) with an instrument such as a transient recorder or a boxcar integrator, and fit the digitized signal to the mathematical function of choice. The data collected following a single excitation would probably have significant statistical fluctuations, so the response from many excitation pulses would be summed until the desired statistical accuracy was achieved, and this summed spectrum fit.

While this approach has been used to collect scintillator timing data, it has limited time resolution. Since an analog sum of the photomultiplier tube response is being accumulated, the time resolution is limited by the width of photomultiplier tube response to a single photon, which is typically 5 ns. A further limit the on time resolution is caused by the minimum bin width on boxcar integrator or transient recorder, which is also about 5 ns.

The delayed coincidence method works by sampling the physical process that underlies the curve in Figure 1a, which is individual scintillation photons arriving at discrete times. The decrease in amplitude with time shown in Figure 1a is really due to the average time between individual photons increasing. Therefore, the delayed coincidence method measures the arrival time (after excitation) of individual scintillation photons. A constant fraction discriminator uses the leading edge of the photomultiplier tube output pulse to generate an accurate timing signal, and the time difference between this pulse and the excitation time is digitized with a time to digital converter (TDC). As the data collected in this manner is really identical to that collected in the previous para-

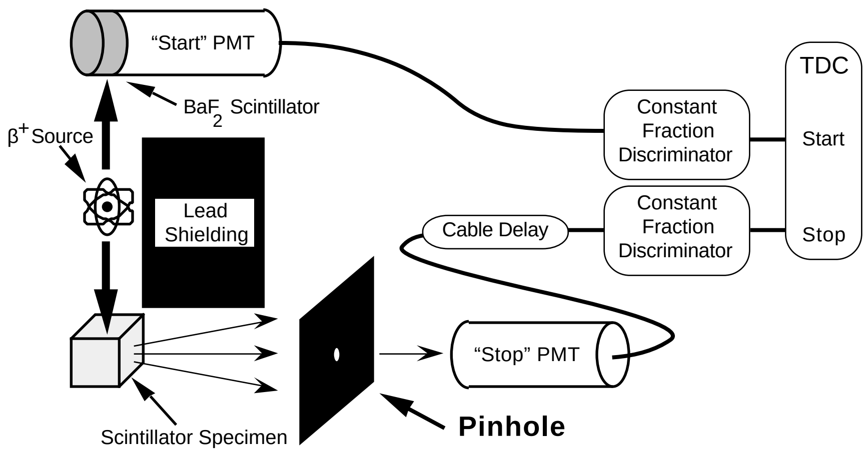

Figure 2: Typical experimental configuration for the conventional delayed coincidence method. The new methods replace the pinhole with a focusing lens.

graph, the response from many excitation pulses would be summed before fitting and the same mathematical fit to decay time would result.

This method improves the timing resolution significantly as compared to the summed analog signal approach described above. The timing uncertainty from the photomultiplier tube is now caused by the timing jitter in the leading edge of the output signal (rather than the width of this signal), which is typically 0.5 ns. Using a TDC has advantages over a boxcar integrator or transient recorder, both because the timing accuracy of TDCs are better (<0.5 ns is typical) and because TDCs tend to be less expensive.

In practice, it is impossible to measure the arrival times of *all* the scintillation photons resulting from a single excitation. This does not affect the data quality as long as the photons whose arrival times are measured are selected in an unbiased way, that is, that the probability of being measured is independent of the arrival time. The reduced data collection efficiency implies that more excitations must be summed over to obtain the same number of measured photons, but the resulting data set, and thus the resulting decay time measurement, would be identical to that collected with the analog summing method (albeit with better time resolution). The difference between the conventional delayed coincidence method and the new methods presented here is the method used to ensure that the photons measured are selected in an unbiased way.

Conventional Method

Figure 2 shows a typical delayed coincidence experimental configuration that employs a modification by Moszynski and Bengtson [2]. The emitted positron annihilates with a nearby electron, producing two back to back 511 keV photons. One of the 511 keV annihilation photons is detected with good efficiency and timing resolution by the BaF_2 scintillator / photomultiplier tube combination, and is converted into a "start" timing pulse with a constant fraction discriminator. The other annihilation photon independently excites the scintillator specimen, which emits fluorescent photons that are detected by the second photomultiplier tube and converted into a "stop" timing pulse by a second constant fraction discriminator whose threshold is set to detect single photons. The time between "start" and "stop" timing pulses is then digitized with a TDC. The cable delay (typically a few hundred nanoseconds) is usually necessary, as most TDCs have difficulty digitizing events with simultaneous "start" and "stop" signals.

A conventional TDC can only digitize the arrival time of the first "stop" pulse to arrive after a "start" pulse. Therefore the inclusion of events that have more than one "stop" pulse per "start" pulse will bias the data, as the later occurring pulses will not be measured with the same probability as the earlier occurring pulses, and lead to inaccurate decay time measurements. The conventional delayed coincidence method minimizes this bias by reducing the scintillation photon flux at the "stop" photomultiplier tube, usually with a pinhole and/or by physical separation. If the flux is adjusted so that ε, defined as the average number of "stop" pulses to arrive in the sampling period after one excitation of the scintillator specimen, is much less than one, then the probability that two or more photons arrive within the TDC sampling period (where the sampling period is defined as the maximum time interval between "start" and "stop" pulses that will be digitized by the TDC) is quite small.

The fraction of biased events obtained with this method can be calculated easily, where an event is defined to be the measurement of the arrival time of one photon. The probability P that *m* photons will be detected after a single excitation is given by the Poisson distribution:

$$P(m:\varepsilon) = \frac{\varepsilon^m e^{-\varepsilon}}{m!} \quad , \tag{1}$$

where ε again is the average number of "stop" pulses to arrive in the sampling period after one excitation of the scintillator specimen. A good event is one in which exactly one photon is observed, so the good event probability *G* is given by:

$$G = P(1:\varepsilon) = \varepsilon\, e^{-\varepsilon} \quad . \tag{2}$$

A biased event is one in which more one photon is observed, so if we assume that ε«1, the biased event probability *B* is given by:

$$B = \sum_{m=2}^{\infty} P(m:\varepsilon) \approx \frac{\varepsilon^2 e^{-\varepsilon}}{2} \quad , \tag{3}$$

and the ratio of biased to unbiased events is given by:

$$B/G \approx \frac{\varepsilon}{2} \quad . \tag{4}$$

Equation 4 implies that the fraction of biased events scales linearly with the data acquisition rate, since for a fixed "start" rate *T*, the data acquisition rate is just ε*T*. In order to achieve a bias fraction of 1%, ε must be 0.02, implying a data collection rate of 0.02*T*. With this method of reducing bias, further improvements in the bias fraction must necessarily come at the expense of reduced data collection rates.

One–Hit Method

Some modern TDCs, commonly referred to as "Multi–Stop" TDCs, are capable of determining whether more than one "stop" pulse arrives in the sampling period after a "start" pulse. With such an instrument, or with a conventional TDC gated by an external circuit performing the same function, events with more than one "stop" pulse can be actively rejected. This active rejection of potentially biasing events allows the scintillation photon flux at the "stop" photomultiplier tube to be increased significantly and the data acquisition rate increased correspondingly. Since this mode of data collection actively selects events that have exactly one "stop" pulse, it is referred to as the "One–Hit" method. A typical experimental setup would be identical to that shown in Figure 2, except that the pinhole is replaced by a focusing lens.

Figure 3 shows a circuit that enables a conventional TDC to operate in one–hit mode, provided that the TDC has "veto" or "enable output" capability. The "start" signal clears both flip-flops, setting both outputs *false* and thus enabling the output of the TDC. The next "stop" signal to arrive causes the output of the first flip-flop to become *true*, but the output of the second flip-flop remains *false*, so the TDC output remains enabled. Any subsequent "stop" signals cause the output of the second flip-flop to become *true*, which disables the TDC. Thus, the TDC output is only

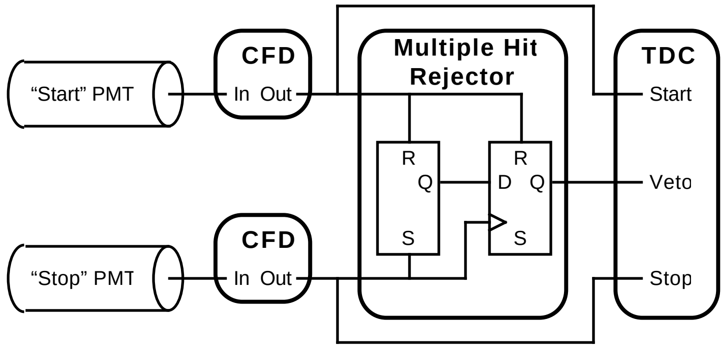

Figure 3: Circuit that enables a conventional TDC to operate in one–hit mode.

enabled when a "start" signal is followed by a single "stop" signal. The circuit shown in Figure 3 should be capable of resolving pulses <10 ns apart if ECL electronics are used.

For a fixed excitation rate T, the data acquisition rate can be maximized using the following argument. Again ε is the average number of photons detected per excitation and Equations 1 & 2 derived above are valid. If we assume that all events with more than one arriving photon are identified and rejected, then there will be no biased events and the data acquisition rate will be maximized when:

$$\frac{\mathrm{d}G}{\mathrm{d}\varepsilon} = 0 = e^{-\varepsilon}(1-\varepsilon) \quad . \tag{5}$$

Equation 5 is solved when ε=1, for which G=0.367 and the data acquisition rate is 0.367T — a value nearly 20 times greater than with the conventional method. Figure 4 plots G, the average number of good events per excitation, as a function of ε. When $\varepsilon \ll 1$, G is equal to ε. As the average number of photons per excitation approaches one, a significant number of excitations result in more than one photon being detected. Since these events are rejected, G becomes less than ε. As ε becomes greater than one, G falls rapidly since most excitations result in more than one photon being detected.

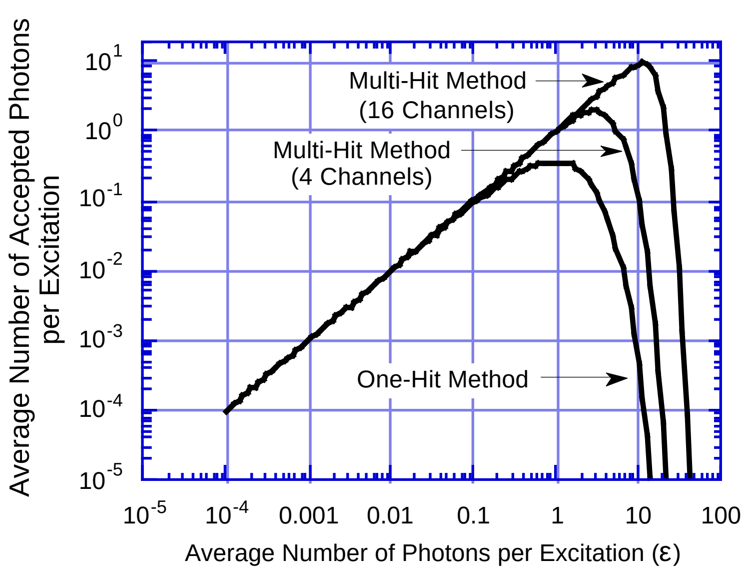

Figure 4: Average number of detected photons accepted per excitation (G) versus the average number of "stop" pulses per excitation (ε).

Multi–Hit Method

Other modern TDCs, commonly referred to as "Multi–Hit" TDCs, are capable of measuring the arrival time of n "stop" pulses per "start" pulse. With such an instrument, the data acquisition rate can be further increased, and if we assume that all arriving photons are identified and their arrival time measured, will also have no bias. Given this assumption G, the average number of photons measured per excitation, is given by

$$G = \sum_{m=1}^{n} mP(m:\varepsilon) = \sum_{m=1}^{n} \frac{\varepsilon^{m} e^{-\varepsilon}}{(m-1)!} . \qquad (6)$$

G will be maximized when

$$\frac{dG}{d\varepsilon} = 0 = \frac{\varepsilon^{n}}{(n-1)!} - \sum_{m=1}^{n} \frac{\varepsilon^{m}}{m!} . \qquad (7)$$

Empirically, this condition is met when $\varepsilon \approx 3n/4$ when $n \geq 2$, at which point the good event rate is approximately $(0.7n - 1)T$. This is an improvement of $(35n - 50)$ over the conventional method and roughly $(2n - 3)$ over the one–hit method. Figure 4 also plots G, the average number of good events per excitation, as a function of ε for n equal to 4 and 16. These curves are similar in shape to the one–hit curve, but extend to much higher event rates. In practice, these large gains in event rate are not achievable due to the pulse overlap of the "stop" pulses, as discussed in the section on Pulse Overlap.

Practical Considerations

Spurious Prompt "Stop" Signals

Although the delayed coincidence method is conceptually simple, good experimental technique is necessary to reduce background events and so the practical considerations discussed in this section must be applied to any of the three methods described above in order to ensure good data quality. A common source of background is scattered 511 keV photons interacting directly in the "stop" photomultiplier tube, which causes a prompt signal that can be misinterpreted as a fast scintillation component. This background is reduced by shielding the "stop" photomultiplier tube with a minimum of 5 cm of lead, especially in the region between the source and the photomultiplier tube. Crosstalk in the photomultiplier tube high voltage power supplies or the constant fraction discriminators can also lead to a spurious prompt signal. Fortunately, the spurious signal rate from all of these sources can be measured by replacing the pinhole or lens in Figure 2 with opaque material (such as aluminum foil) and collecting data. The opaque material blocks all of the scintillation photons coming from the sample (*i.e.* the true signal), but does not affect the 511 keV photons interacting in the photomultiplier tube or the electronic crosstalk (*i.e.* the spurious signals), and so an accurate background spectrum can be acquired.

Multiple Excitations

Another source of bias is events in which a second 511 keV photon interacts in the scintillator sample during the TDC sampling period. Since it is difficult, if not impossible, to know the rate at which annihilation photons excite the specimen scintillator, this situation is usually reduced by limiting the average time between "start" pulses to be much longer than the TDC sampling period. This limitation is eliminated when a controllable excitation source is used, such as a pulsed laser or pulsed x-ray source.

Dark Current and Random Coincidences

There are two unavoidable sources of background events — random coincidences between the "start" and "stop" signals and dark photoelectron emission in the "stop" photomultiplier tube. However, the experimenter has the ability to minimize these sources of background, as seen in the equations below. The rate T at which the "start" photomultiplier tube produces a "start" signal is

$$T = SP_{\mathrm{trig}} \quad , \tag{8}$$

where S is the strength of the positron emitting source (positron annihilations per second) and P_{trig} is the probability that an annihilation results in a "start" signal. Note that P_{trig} includes the probability that an annihilation photon impinges on the trigger scintillator, the probability that this impinging photon interacts in the trigger scintillator, and the probability that this interaction yields a signal above the constant fraction discriminator threshold level. Similarly, the rate R at which the "stop" photomultiplier tube produces a "stop" signal is

$$R = SP_{\mathrm{int}}\varepsilon + R_{\mathrm{D}} \quad , \tag{9}$$

where P_{int} is the probability that an annihilation results in an interaction in the scintillator sample, ε again is the average number of scintillation photons detected in the "stop" photomultiplier tube per interaction, and R_{D} is the "stop" rate due to dark current in the "stop" photomultiplier tube. Note that P_{int} includes the probability that an annihilation photon impinges on the scintillator sample and the probability that this impinging photon interacts in the sample. The true signal rate is given by

$$\text{Signal Rate} = SP_{\mathrm{geom}}P_{\mathrm{trig}}P_{\mathrm{int}}\varepsilon \quad , \tag{10}$$

where P_{geom} is the probability that an annihilation photon is incident on the scintillator sample given that the other annihilation photon is incident on the trigger scintillator. The background rate is

$$\text{Background Rate} = TR\Delta t = (SP_{\mathrm{trig}})(SP_{\mathrm{int}}\varepsilon + R_{\mathrm{D}})\Delta t \quad , \tag{11}$$

where Δt is the sampling period. Dividing Equation 11 by Equation 10, we find that the background fraction in the data set due to random coincidences and photomultiplier tube dark current is

$$\frac{\text{Background Rate}}{\text{Signal Rate}} = \frac{\Delta t}{P_{\mathrm{geom}}}\left[S + \frac{R_{\mathrm{D}}}{P_{\mathrm{int}}\varepsilon}\right] \tag{12}$$

Equation 12 guides the experimenter in minimizing the background contamination. The geometrical factors P_{int} and P_{geom} should be maximized, that is, the scintillator sample should be as large as possible to maximize probability of the 511 keV photons interacting in it, and the scintillator sample, positron source, and trigger scintillator should be well aligned. The dark current in the "stop" photomultiplier tube should be minimized, which can be done by cooling the photomultiplier tube. The minimum source strength possible should be used, although this obviously increases the data collection time. The sampling period Δt is usually determined by the decay time of the specimen scintillator, and so is not adjusted to reduce background.

Dynamic Range

To measure the decay time of a scintillator accurately, the bin width of the TDC should be at least ten times shorter than the shortest decay component and the dynamic range of the TDC three times longer than the longest decay component. This results in a large number of bins, especially if the longest and shortest decay components are significantly different. To cite an extreme example, at –80° C the shortest decay component of CsI(Tl) is <0.5 ns and the longest is 18 µs [3]. This implies a data set of 360,000 bins, each 0.05 ns wide! While there are TDCs available with a 24 bit dynamic range that can accumulate this many bins, the resulting data set would be at least half of a megabyte in size, which is large enough to cause difficulty accumulating, storing, and fitting the data.

There are two methods for reducing the size of this data set, both based on the fact that a small bin width is not necessary at long times. One method is to take two (or more) data sets, one with a small bin width that spans only the shorter decay components and one with wide time bins that spans the full dynamic range, and fit the two data sets simultaneously. This method has the disadvantages that it doubles the acquisition time (two data sets must be accumulated) and can lead to systematic errors if care is not taken in the fitting process. A more attractive method is to accumulate data with a small bin width that spans the entire dynamic range, but rebin the data in bins with exponentially increasing width. A computationally efficient way to accomplish this is to define a compressed bin index, which is the logarithm (base 2) of the bin number, and accumulate the data in these compressed bins. This logarithm can be computed with several shifts and adds, and takes less than 50 µs on a Macintosh IIfx computer.

Pulse Overlap

The estimates for the fraction of biased events made in the One–Hit and Multi–Hit sections are all based on the assumption that the detection electronics is able to resolve each scintillation photon pulse in the “stop” photomultiplier tube. This assumption is valid in the conventional method, as the photon flux at the “stop” photomultiplier tube is artificially limited to «1 “stop” pulse per excitation. The photon flux with the one–hit and multi–hit methods is significantly greater, and events with greater than one “stop” pulse per excitation are common. It therefore is possible that the difference in arrival time of two “stop” pulses is less than the dead time of the constant fraction discriminator or TDC, and so only the first “stop” pulse will be detected and its arrival time measured. This pulse overlap constitutes another form of event bias that eventually limits the maximum event rate of the one–hit and multi–hit methods.

The following sections estimate the effect of this pulse overlap for the two new methods. We assume that the scintillator sample emits photons with a single exponential decay time τ, and that the electronics are characterized by a single non–paralyzing dead time DT. For convenience we define δ to be the ratio of the dead time to the decay time, or

$$\delta = \frac{\mathrm{DT}}{\tau} \quad . \tag{13}$$

One–Hit Method

With the one–hit method, a biased event occurs only when m photons are detected and all m arrive within time DT of the first photon to arrive. This probability is the product of Equation 1 and the probability that all m photons arrive within time DT of the first photon, or

$$\mathrm{P}(m:\varepsilon)\mathrm{P}(\text{all} < \mathrm{DT}) = \frac{\varepsilon^m e^{-\varepsilon}}{m!}(1-e^{-\delta})^{m-1} \quad . \tag{14}$$

The ratio of biased events to good events is then

$$B/G = \frac{\sum_{m=2}^{\infty} m\mathrm{P}(m:\varepsilon)\mathrm{P}(\text{all} < \mathrm{DT})}{\varepsilon\, e^{-\varepsilon}} \approx \frac{\varepsilon}{2}(1-e^{-\delta}) \quad . \tag{15}$$

where the approximation is valid for δ«1 and $\varepsilon \le 2$, which is true in most situations. Figure 5 plots the fraction of biased events $B/(B+G)$ as a function of ε for several values of δ. While Equation 5 indicates that the maximum data collection rate is achieved when ε=1, Figure 5 shows that collecting data at such a rate will result in a bias fraction >0.01 unless the dead time DT is less than 2% of the scintillator decay time τ. Reducing the average number of photons ε can relax the requirements on δ significantly without having as large an impact on the data collection rate. For example,

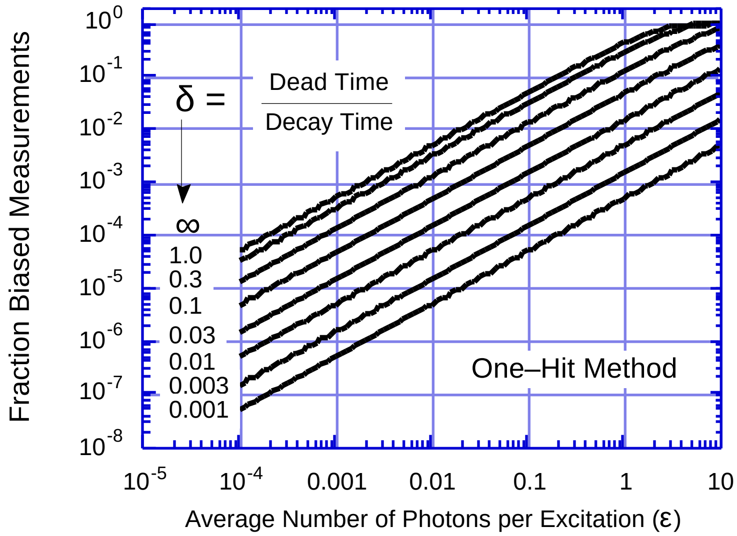

Figure 5: Fraction of biased photons detected per excitation versus the average number of photons per excitation (ε) for several values of δ when using the one–hit method. In this case, biased events are due to pulse overlap.

reducing ε from 1 to 0.1 results in a bias fraction of 0.01 with δ=23% (*i.e.* an order of magnitude increase in the allowable dead time), while only reducing the data acquisition rate by a factor of 4.

Multi–Hit Method

With the multi–hit method, biased data occurs when there are m "stop" pulses and any one of them arrives within time DT of the previous "stop" pulse. This probability is the product of Equation 1 and the probability that any of the m pulses arrive within time DT of the previous pulse, or

$$P(m:\varepsilon)P(\text{any} < \mathrm{DT}) = \frac{\varepsilon^m e^{-\varepsilon}}{m!}\left(1 - e^{-\frac{m!\delta}{2(m-2)!}}\right) \quad . \tag{16}$$

The probability for unbiased data is

$$P(m:\varepsilon)P(\text{none} < \mathrm{DT}) = \frac{\varepsilon^m e^{-\varepsilon}}{m!} e^{-\frac{m!\delta}{2(m-2)!}} \quad , \tag{17}$$

so the ratio of biased events to unbiased events is

$$B/G = \frac{\sum_{m=2}^{\infty} mP(m:\varepsilon)P(\text{any} < \mathrm{DT})}{\sum_{m=1}^{\infty} mP(m:\varepsilon)P(\text{none} < \mathrm{DT})} \quad . \tag{18}$$

Figure 6 plots the fraction of biased events $B/(B+G)$ as a function of ε for several values of δ, assuming a 16 channel multi–hit TDC (*i.e.* n=16). While Equation 7 indicates that a very high data collection rate is achieved when ε≈3n/4=12, Figure 6 shows that collecting data at such a rate always results in a large bias fraction, even when the dead time DT is less than 0.1% of the scintillator decay time τ. The average number of photons ε must be reduced significantly in order to

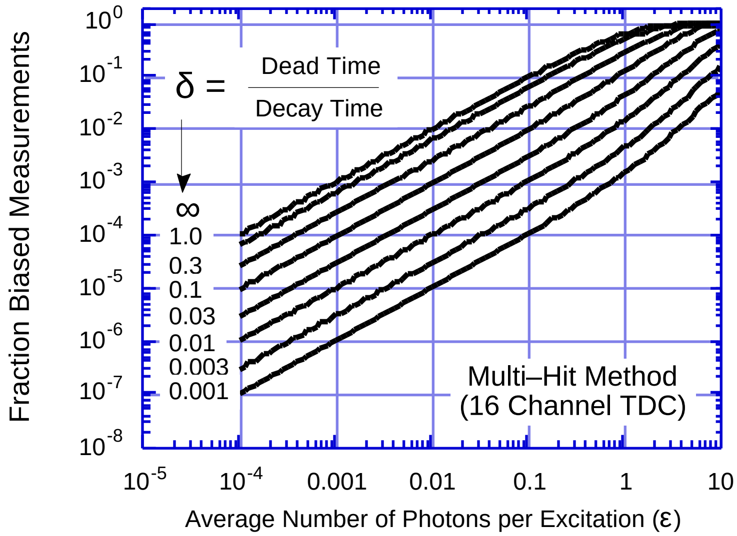

Figure 6: Fraction of biased photons detected per excitation versus the average number of photons per excitation (ε) for several values of δ when using the multi–hit method with a 16 channel TDC. In this case, biased events are due to pulse overlap.

achieve reasonably unbiased data. For a given δ, the value of ε necessary to achieve a given bias fraction is typically a factor of 3 less than with the one–hit method. This is due to the fact that with the one–hit method, data is only biased by “stop” pulses that overlap with the *first* photon, while the multi–hit method is biased by *any* “stop” pulses that overlap.

Experimental Verification

In order to verify that the techniques described above perform as expected, the decay time spectrum of the same piece of scintillator was measured with each of the three methods. The scintillator chosen was a 1 cm cube of bismuth germanate (BGO), a commonly used material for gamma ray detection whose decay time has been measured by a number of researchers [4, 5, 6, 7, 8]. At room temperature (+25˚ C), the majority of the fluorescent photons (90%) are emitted with a 300 ns decay time, while the remaining 10% are emitted with a 60 ns decay time [7].

A BaF_2 scintillator coupled to a Hamamatsu R-2059 photomultiplier tube provided a “start” signal, and another R-2059 photomultiplier tube placed 50 cm away from the sample provided the “stop” signal. The “stop” photomultiplier tube was in a thermally insulated, temperature controlled housing kept at –20˚ C to reduce dark current. A 0.3 mCi ^{68}Ge source provided the 511 keV photon pairs that excited both the BaF_2 scintillator and the BGO scintillator sample. Timing signals from both photomultiplier tubes were generated using a Tennelec TC-454 constant fraction discriminator (CFD), and the time difference between the start and stop signals was digitized a LeCroy 2277 TDC. A level translator was used to convert the NIM level outputs from the CFD to the ECL level inputs required by the TDC. The dead time DT for the system is 24 ns, limited by the level translator. It is possible to reduce the dead time of the level translator and TDC to the 2–6 ns range, at which point the system dead time would be limited by the photomultiplier tube.

The LeCroy 2277 TDC is a “Multi–Hit” TDC, but is able to mimic “conventional” and “Multi–Stop” TDCs by selectively retaining only a portion of the data that the module provides. A “conventional” TDC can be simulated if only the first “stop” signal (for each “start” signal) is retained and data from subsequent “stop” signals is ignored. A “Multi–Stop” TDC is mimicked if the data from the first “stop” signal is retained only if a second “stop” signal is absent. Thus, timing spectra can be acquired in all three modes using identical hardware merely by making a software change in the data acceptance criteria.

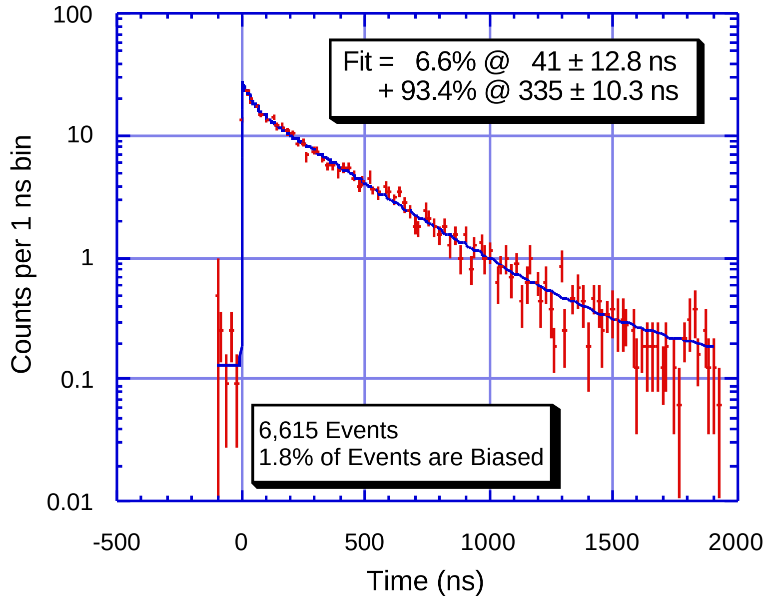

Figure 7: Scintillation decay time spectrum of BGO measured with the conventional method. Data were accumulated for 60,000 seconds, during which 6,615 events were collected, of which 1.8% were biased.

Figure 7 shows the decay time spectra obtained with the conventional method. Since this TDC is able to identify “start” pulses with more than one “stop” pulse, the number of “start” pulses with 1 and 2 “stop” pulses can be measured directly, and their ratio used with Equation 1 to infer the value of ε. Therefore, the size of the pinhole was adjusted so that ε=0.036, yielding a 1.8% bias fraction, and data were collected for 60,000 seconds of live time. Note that the dead time eliminated in this live time correction is the time consumed by the computer reading out the TDC.

A total of 6,615 events were collected during this 60,000 seconds of acquisition. These data were fit to the sum of two exponential decay components plus a constant background term, and the decay times, fraction of the two decay components, and background level adjusted to minimize the mean squared deviation between the fit curve and the data. The resulting fit, which is also displayed in Figure 7, finds that 6.6% of the scintillation photons are emitted with a 41±13 ns decay time and 93.4% are emitted with a 335±10 ns decay time, in good agreement with previously published values.

The pinhole was replaced with a focusing lens and data acquisition program configured to acquire data in the one–hit mode. Again, the ratio of “start” signals with 1 or 2 “stop” signals was used to determine ε, and the geometry was adjusted so that the fraction of biased events, as determined by Equation 15, was 1.9% (*i.e.* the same as with the conventional method, obtained with ε=0.507). Data was again accumulated for 60,000 seconds, and the results shown in Figure 8. A total of 80,307 events were collected during this acquisition period — a data collection rate twelve times higher than the conventional method. The data is fit using the method described in the previous paragraph, resulting in a determination that 7.3% of the scintillation photons are emitted with a 42±3.6 ns decay time and 92.7% are emitted with a 323±3.0 ns decay time.

Finally, the data acquisition program configured to acquire data in the multi–hit mode, the ratio of “start” signals with 1 or 2 “stop” signals was used to determine ε, and the geometry was adjusted so that the fraction of biased events, as determined by Equation 18, was 1.8% (*i.e.* the same as with the previous two methods, obtained with ε=0.22). Data was again accumulated for 60,000 seconds, and the results shown in Figure 9. A total of 52,835 events were collected during this acquisition period — eight times more than with the conventional method, but somewhat less than with the one–hit method. The data is fit using the method described previously, resulting in a determination that 7.2% of the scintillation photons are emitted with a 51±5.9 ns decay time and 92.8% are emitted with a 337±4.2 ns decay time.

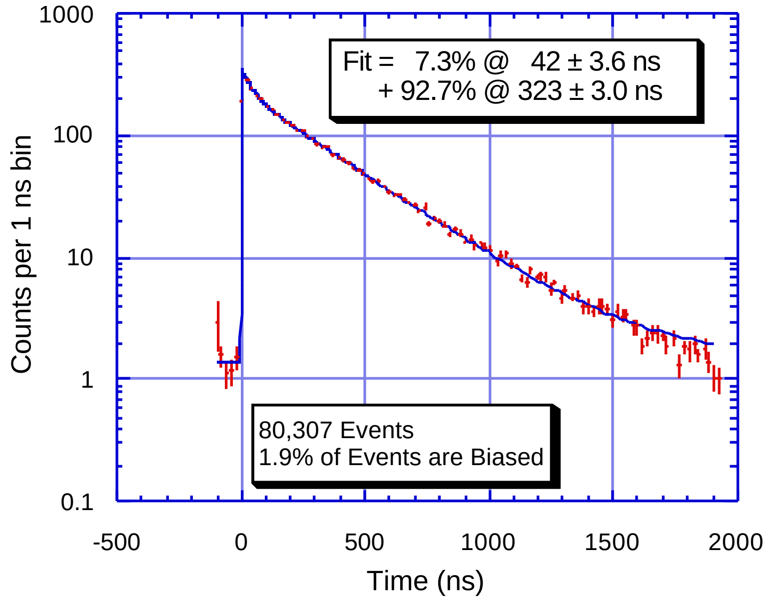

Figure 8: Scintillation decay time spectrum of BGO measured with the one–hit method. Data were accumulated for 60,000 seconds, during which 80,307 events were collected, of which 1.9% were biased.

The previous measurements show that substantial increases can be made in the data collection rate, and the fact that the decay lifetimes and fractions obtained with all three methods agree within statistical errors indicates that this increase does not affect the data quality. In this counting situation, the highest data collection rate (for a given fraction of biased events) is obtained with the one–hit method, as the reduction in ε necessary to reduce the bias with the multi–hit method more than cancels the gain in data collection rate achieved by digitizing >1 “stop” pulse per “start” pulse.

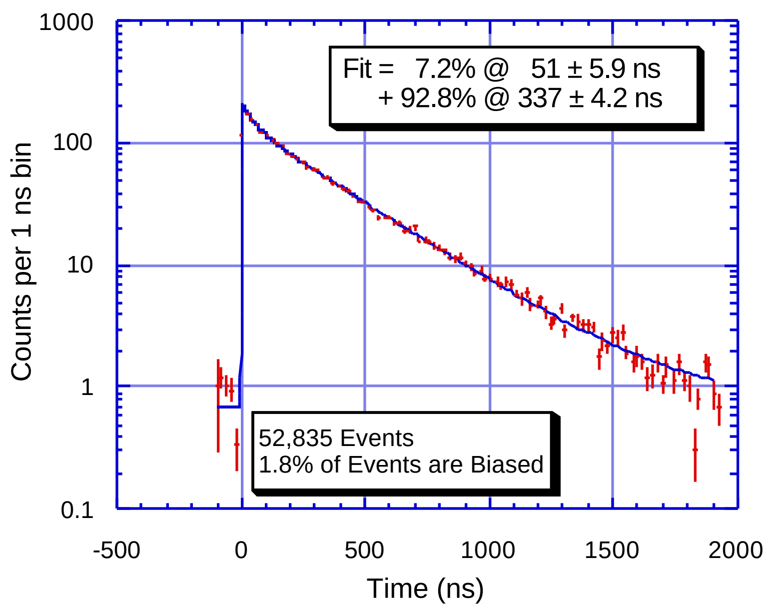

Figure 9: Scintillation decay time spectrum of BGO measured with the multi–hit method. Data were accumulated for 60,000 seconds, during which 52,835 events were collected, of which 1.8% were biased.

Conclusion

Two methods have been proposed for increasing the data collection rate when using the delayed coincidence method. The methods rely on modern TDCs to detect the presence of, or measure the arrival time of, photons that would ordinarily bias the data. This increases the data collection rate since the conventional delayed coincidence method must greatly reduce the photon flux in order to minimize this bias. Formulas predicting the fraction of biased events have been derived, and the validity of the method has been demonstrated experimentally. For the range of scintillation decay times and apparatus dead times considered here, the one–hit method provides the highest data acquisition rate.

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